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WATERTOWN ARSENAL LABORATORY

MEMORANDUM REPORT

NO. WAL 710/624

Metallurgical Examination of 4-5" Thick
Rolled Homogeneous Armor Plate

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BY
E. L. REED
Research Metallurgist

AUG 10 1944

DATE 26 April 1944

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Final Report on Problem B-4, 29

26 April 1944

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Rolled Homogeneous Armor Plate

ABSTRACT

Metallurgical examination, including fracture tests for steel soundness, hardness traverse, Jominy hardenability test, chemical analyses, V-notch Charpy impact tests, macroscopic and microscopic examination, was made on four plates tested at the Ordnance Research Center on a program for the development of 4" and 5" thick armor plate. Two plates, 4" and 5" thick, were submitted by the Carnegie-Illinois Steel Corp. whereas one 4" thick plate was submitted by the Gary Armor Plate Plant and one plate of the same thickness was submitted by the Great Lakes Steel Corp. All plates were of satisfactory steel soundness.

The hardenability of the Carnegie-Illinois compositions was adequate for the 4-5" thick plate involved but the hardenability of the Gary Armor Plate Plant and the Great Lakes Steel plates was inadequate for the manufacture of satisfactory 4" thick plate. The hardness of the plates investigated was uniform across the sections.

1. As requested by the Ordnance Research Center, Aberdeen¹, metallurgical examination has been completed on four (4) samples of homogeneous rolled armor plate varying in thickness from 4-5" as described below:

1. APG 470.5/4675, Wtn 470.5/7947(r), dated 24 February 1944.

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a. Sample No. A - 4" thick, Gary Armor Plate Plant. This plate was acceptable under Specification AXS-488, Revision 1 but failed to meet the requirements of Specification AXS-488, Revision 2 since it gave an excessive exit diameter (without spalling) on the 90 mm. A.P. M77 projectile-through-plate test - APG Report No. A12564.

b. Sample No. B - 5" thick Carnegie-Illinois plate. This plate had good ballistic properties under the impacts of 75 mm. M72 A.P. and 90 mm. M77 A.P. projectiles at normal obliquity - APG Report No. A12353.

c. Sample No. C - 4" thick Carnegie-Illinois plate. This plate had good ballistic properties under the impacts of 75 mm. M72 A.P. and 90 mm. M77 A.P. projectiles at normal obliquity - APG Report No. A12353.

d. Sample No. D - 4" thick Great Lakes plate. This plate was tested under Specification AXS-488, Revision 1 and AXS-488 Revision 2. The plate at 207 Brinell hardness gave excessive exits (without back spalling) under the 90 mm. A.P. M77 projectile-through-plate test - APG Report No. A12563.

2. Metallurgical examination consisted of the following tests.

- a. Chemical analyses.
- b. Fracture tests for steel soundness.
- c. Jominy hardenability tests.
- d. Hardness traverse.
- e. V-notch Charpy impact tests.
- f. Macroscopic examination.
- g. Microscopic examination.

3. The results of the above tests in detail are presented below:

a. Chemical Analyses.

The chemical analyses are reported in Table I.

Table I

Chemical Analyses

Plate No.	Manufacturer	Chemical Composition													
		C	Mn	Si	S	P	Fe	Cr	Mo	V	Cu	Al	Ti	Zr	B
A-4 ^a	Gary Armor	.28	1.57	.32	.027	.017	.63	1.06	.49	Trace	.09	.04	.05	Nil	.0013
B-5 ^a	Carnegie-Illinois	.33	.18	.05	.021	.015	3.94	1.76	Nil	Trace	.04	.008	Trace	Trace	.0010
C-4 ^a	Carnegie-Illinois	.35	.16	.05	.018	.020	3.68	1.54	Nil	Trace	.05	.01	Trace	Nil	.0009
D-4 ^a	Great Lakes	.30	1.24	.69	.019	.019	Trace	.78	.32	Trace	.06	.015	Trace	.13	.003

The Gary Armor plate No. A and the Great Lakes plate No. D are low alloy type steels treated with boron whereas the 5" and 4" thick Carnegie-Illinois plates No. B and C are high alloy plates which were not treated with the element boron. The amount of boron in the plate manufactured by the Great Lakes Steel Corporation is slightly excessive for best results from the point of view of toughness of the steel.

b. Fracture Test for Steel Soundness.

Fracture test samples, approximately 8" long and 4-5" wide, were cut from the transverse direction of the plates, nicked perpendicularly to the longitudinal axis to such a depth as to leave a solid section 1" in width and broken slowly under a press. This additional notching, which was necessary due to inadequate lengths of the samples, provided additional stress concentrations, thereby promoting greater tendencies to form crystallinity in the samples tending to produce brittle fractures.

The steel quality of samples A, B and C was satisfactory, in fact, these samples had a "B" rating as specified in Specification AXS-488, Revision 2. Sample No. D exhibited a crystalline fracture and, therefore, the steel quality could not be determined in this particular sample.

Samples were not available for the fibre fracture test, therefore, the fibre fracture ratings were made on the fractures for steel soundness as follows:

Plate No.	Manufacturer	Fibre Test
A	Gary Armor	Predominantly fibrous, patches of crystallinity
B	Carnegie-Illinois	Fibre
C	Carnegie-Illinois	Fibre
D	Great Lakes	Crystalline

c. Jominy Hardenability Tests.

The Jominy hardenability curves of the four plates are shown in Figures 1 and 2.

Since these Jominy bars were given a long austenitization treatment (identical with the manufacturer's heating cycles), it was necessary to grind the bars to a depth of .050" in order to obtain the true hardness readings.

The results of the end quench tests are tabulated in Table II.

Table II

Results of End Quench Tests

<u>Sample No.</u>	<u>Rockwell C Hardness at Depth of</u>		
	<u>1/16"</u>	<u>20/16"</u>	<u>40/16"</u>
A 4" Gary Armor	52.0	49.0	48.0
B 5" Carnegie-Illinois	56.0	53.0	52.0
C 4" Carnegie-Illinois	56.5	53.0	53.0
D 4" Great Lakes	53.0	50.5	45.0

The difference in the hardness levels between the end quenched Carnegie-Illinois samples, the Gary Armor, and the Great Lakes Steel test bars is due to the lower carbon content of the latter two. A survey of the Jominy curves and the data in Table II indicates that the Carnegie-Illinois samples, Nos. B and C have excellent hardenability. Essentially full hardening is maintained at the slow cooled end of these Jominy bars, reference the martensitic structure in the series of photomicrographs attached to Figures 1 and 2. This indicates that with respect to quench hardening or transformation to the high temperature transformation products of ferrite and pearlite, these analyses would be satisfactory in thicknesses up to at least 4" to 5" upon water quenching.

Although the Jominy curve of Gary Armor plate No. A indicates satisfactory hardenability, microscopic analysis of the air cooled end of the bar indicates a transformation of the austenite into some intermediate temperature transformation products, see Figure 1. This indicates that the alloy content of this plate is such that objectionable intermediate temperature transformation products would be obtained in the center of a 4" thick plate of this composition. These constituents were found in the tempered condition in the sample of the plate submitted, see Figure 6.

The Jominy curve of the Great Lakes Steel Corporation plate No. D shows a decrease in hardness from 20/16" to 40/16". This is correlated with a greater amount of intermediate temperature transformation products at the slowly cooled end of the Jominy bar than found in the Gary Armor sample. Furthermore, a microscopic study of this bar shows the presence of some carbide at the quenched end and also at 20/16".

The results of this test indicates that the Great Lakes composition has inadequate hardenability for the manufacture of 4" thick plate. It should be noted that a large amount of tempered intermediate transformation products were evident in the sample of the Great Lakes plate, see Figure 6.

d. Brinell Hardness Survey.

The results of the hardness surveys made on cross sections of the samples are summarized in Table III. The series of individual hardness readings are given in Table 1A in Appendix A.

Table III

Summary of Brinell Hardness Surveys

<u>Plate No.</u>	<u>Average Brinell Hardness Values</u>			<u>Reported by Mfr.</u>
	<u>Series 1</u>	<u>Series 2</u>	<u>Series 3</u>	
A - 4" Gary Armor	256	255	255	255/269
B - 5" Carnegie-Illinois	243	241	243	---
C - 4" Carnegie-Illinois	229	229	230	---
D - 4" Great Lakes	207	207	208	229/241

As noted in the above table, the hardness values are uniform on the cross sections of each individual plate.

The hardness of the Gary Armor plate No. A as obtained in this laboratory agrees very closely with that reported by the manufacturer. On the other hand, the hardness values reported by the Great Lakes Steel Corporation on plate No. D were 22-34 points higher than those determined at Watertown Arsenal.

No hardness readings were reported by Carnegie-Illinois Steel Corporation on plates, Nos. B and C.

e. V-notch Charpy Impact Tests.

The results of the V-notch Charpy impact tests are given in Table IV.

Table IV

V-notch Charpy Impact Tests

Foot - Pounds

<u>Plate No.</u>	<u>+70°F</u>	<u>*Fracture</u>	<u>-40°F</u>	<u>*Fracture</u>	<u>Ave. Brinell Hardness</u>
A - 4" Gary Armor	46.9	Fc	23.4	Cd	256
B - 5" Carnegie-Illinois	58.3	F	58.2	F	242
C - 4" Carnegie-Illinois	63.0	F	52.9	F	229
D - 4" Great Lakes	68.5	Fc	32.7	Cd	207

*Fracture

Fc - Fibrous, mixed with spots of crystallinity

F - Fibrous

Cd - Dull crystalline (complete)

The considerable changes in impact values of the Gary Armor and Great Lakes Steel materials with a lowering of the test temperature correlate with the tendency towards brittle failures observed in the fracture tests. The presence of intermediate temperature transformation products upon quenching, as revealed by the Jominy end-quench test results and by the microscopic examination of the heat treated structures, is undoubtedly the cause of this undesirable behavior. On the other hand, high impact values were retained in the nickel-chromium steel plates at the -40°F temperature, correlating with the fibrous fractures and the absence of intermediate or high temperature transformation products found upon quenching. The Great Lakes Steel plate, if of satisfactory microstructure, would yield considerably higher impact values at the low hardness involved.

f. Macrostructure

The macrostructure of the longitudinal and transverse sections of the plates after etching in hot acid is shown in Figure 3.

The Gary Armor plate No. A and the Great Lakes plate No. D are fairly free from segregations whereas the Carnegie-Illinois plates, Nos. B and C contain some segregations of nonmetallic inclusions.

The pattern observed in the macroetched sections of both Carnegie-Illinois plates indicates that these plates were finished under a forging press.

G. Microstructure

Photomicrographs illustrating the distribution of the non-metallic inclusions and also the typical microstructures of the plates are presented in Figures 4, 5, and 6.

With the exception of the 5" and 4" thick Carnegie-Illinois plates, Nos. B and C, the plates examined were free from pronounced segregation of nonmetallic inclusions.

A series of fine oxide-sulphide groups of nonmetallic inclusions was present in the longitudinal section of the 4" thick Gary Armor plate No. A while an occasional group of alumina inclusions was present in the transverse section of the plate. The segregation revealed in the macrostructure of the 5" thick Carnegie-Illinois plate No. B consisted of complex oxide-sulphide inclusions whereas oxide inclusion streaks were found in the 4" thick plate No. C, manufactured by the same company. Considerable amounts of scattered fine oxides mixed with zirconium-nitride inclusions were present in the 4" thick Great Lakes plate No. D.

The microstructure of the 4" thick Gary Armor plate No. A consisted of fine tempered intermediate and low temperature transformation products and an occasional ferrite-carbide grain boundary aggregate. The 5" and 4" thick Carnegie-Illinois plates, Nos. B and C had a microstructure consisting of tempered low temperature transformation products and a trace of ferrite. Tempered intermediate temperature transformation products, ferrite and occasionally some spheroidized carbide, were evident in the microstructure of the 4" thick Great Lakes plate No. D.

NOTE: Photomicrographic work conducted by M. Yoffa.

4. Correlations were established between the fibre characteristics, V-notch Charpy values and the microstructure of the plates. The low temperature transformation products detected in the high alloy Carnegie-Illinois plates B and C appear to have fairly good V-notch impact properties and yield a fibrous fracture. On the other hand, the low alloy plates manufactured by the Gary Armor Plate Plant and the Great Lakes Steel Corporation had poor V-notch impact properties, especially at sub-zero temperatures which were associated with crystallinity in the fracture test and intermediate temperature transformation products.

The Carnegie-Illinois composition had adequate hardenability for 4-5" thick armor whereas the Gary Armor and the Great Lakes Steel Corporation analyses contained insufficient alloy for the necessary hardenability for 4" thick plate.

The Brinell hardness of the four plates was uniform across the section and varied from plate to plate as follows, Gary Armor - 255 Brinell Carnegie-Illinois. 5" thick - 242 Brinell, Carnegie-Illinois 4" thick, 229 Brinell and Great Lakes, 4" thick, 208 Brinell.

E. L. Reed

E. L. REED

Research Metallurgist

APPROVED:

N. A. MATTHEWS
Major, Ord. Dept.
Chief, Armor Section

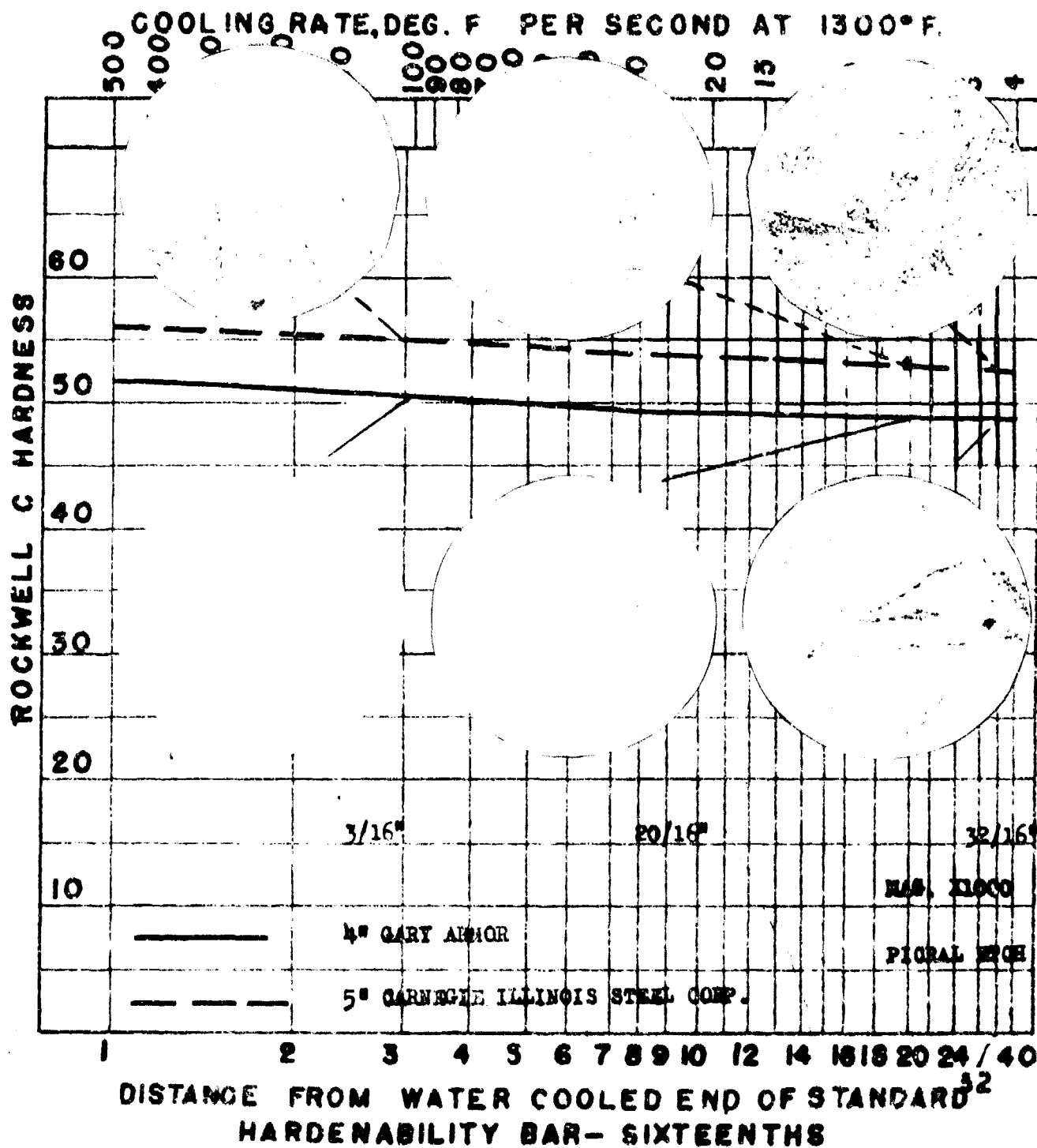


PLATE		CHEMICAL COMPOSITION											
NO.	C	MN	SI	S	P	NI	CR	MO	CU	AL	ZR	TI	B
A	.28	1.57	.32	.027	.017	.63	1.06	.49	.09	.01	NIL	-	.0013
B	.33	.18	.05	.021	.015	3.94	1.76	NIL	.04	.008	-	TR.	.0010

PLATE		HEAT TREATMENT	
NO.		TEMP. °F	QUENCH
A	=====	1650	RISE 6-1/2 SOAK 3-1/6
B	=====	1570	5 4-1/2

FIGURE 1

500 CO
500 CO



FIGURE 2

LONGITUDINAL

TRANSVERSE



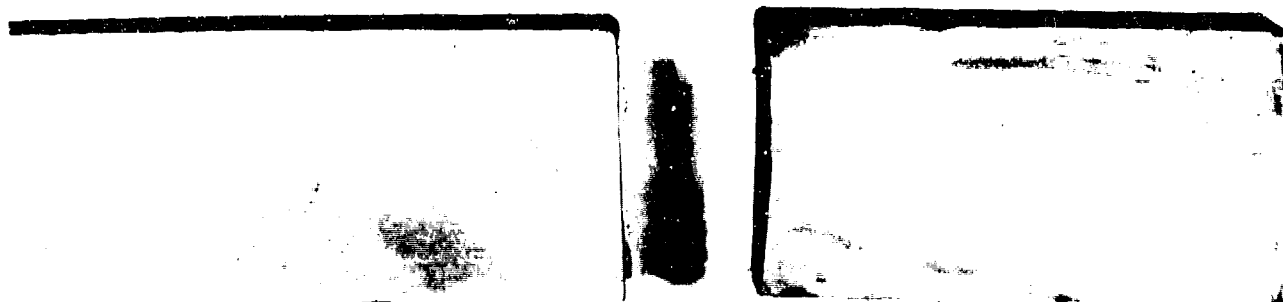
A - GARY ARMOR PLATE - 4" THICK



B - CARNEGIE ILLINOIS - 5" THICK



C - CARNEGIE ILLINOIS - 4" THICK



D - GREAT LAKES - 4" THICK

MACROSTRUCTURE OF 4" - 5" THICK ROLLED ARMOR PLATE
14 MARCH 1944 WTN.780-2289

FIGURE 3

Nonmetallic Inclusions in 4-5" Thick Rolled Armor

Longitudinal

Transverse

No. A
4" Gary Armor
Typical fine manganese sulphides
(gray) and oxides (dark).

No. A
4" Gary Armor
Isolated group of alumina inclusions.

No. B
5" Carnegie-Illinois
Typical inclusion stringer similar to
the sulphide-oxide type.

No. B
5" Carnegie-Illinois
Typical round inclusion similar to
the sulphide-oxide type.

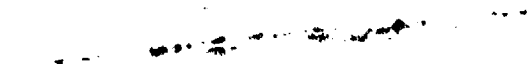
Photomicrographs X100 - Unetched

FIGURE 14

Nonmetallic Inclusions in 4-5" Tank Rolled Armor

Longitudinal

Transverse



No. C

4" Carnegie-Illinois

Typical alumina inclusion streak.

No. C

4" Carnegie-Illinois

Typical inclusions found in section.

No. D
4" Great Lakes
Typical group of zirconium nitrides
and other complex nonmetallics.

No. D
4" Great Lakes
Typical group of zirconium nitrides
and other complex nonmetallics.

Photomicrographs X100

FIGURE 5

Microstructure of 4-5" Thick Rolled Armor



No. A
4" Gary Armor
Tempered intermediate temperature transformation products, ferrite-carbide aggregate.



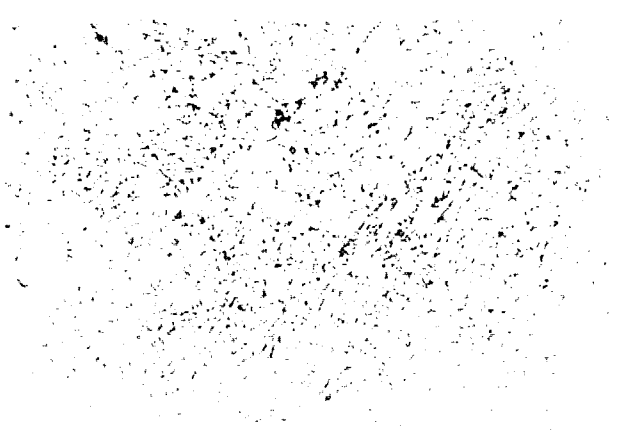
No. A
4" Gary Armor
Another area showing tempered intermediate and lower temperature transformation products.



No. B
5" Carnegie-Illinois
Tempered lower temperature transformation products with traces of ferrite.



No. C
4" Carnegie-Illinois
Tempered lower temperature transformation products with traces of ferrite.



No. D
4" Great Lakes
Tempered intermediate temperature transformation products and ferrite.



No. D
4" Great Lakes
Another area, tempered intermediate temperature transformation products, traces of ferrite and some large spheroidized carbides.

Photomicrographs X1000 - Picral Etch

FIGURE 6

APPENDIX A

Three series of Brinell hardness readings were made on the cross sections of the four samples at intervals of about one inch apart. The values are reported in Table 1A.

Table 1A

Plate A 4" Gary Armor			Plate B 5" Carnegie-Illinois			Plate C 4" Carnegie-Illinois			Plate D 4" Great Lakes		
Traverse			Traverse			Traverse			Traverse		
<u>1</u>	<u>2</u>	<u>3</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>1</u>	<u>2</u>	<u>3</u>
255	255	255	241	235	241	235	235	235	207	207	212
255	255	255	241	241	241	229	229	229	207	207	207
248	248	248	235	235	235	223	223	223	207	207	207
262	255	255	248	248	248	229	229	235	207	207	207
<u>262</u>	<u>262</u>	<u>262</u>	<u>248</u>	<u>248</u>	<u>248</u>	<u>229</u>	<u>229</u>	<u>229</u>	<u>207</u>	<u>207</u>	<u>207</u>
Ave. 256	255	255	243	241	243	229	229	230	207	207	207
Grand Ave. 255			242			229			208		